

On the effective action of D-brane-anti-D-brane system

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ABSTRACT

We examine the proposal for constructing the effective action of a D_p -brane-anti- D_p -brane system from the non-abelian extension of tachyon DBI action. We consider two prescriptions for the trace in the non-abelian tachyon DBI action. The usual trace and the symmetric trace prescription. The former gives an action for the $D_p\bar{D}_p$ system which reduces to the action proposed by A.Sen for coincident branes. The latter gives a different action which is consistent with the S-matrix element calculations.

1 Introduction

Study of unstable objects in string theory might shed new light in understanding properties of string theory in time-dependent backgrounds [1, 2, 3, 4, 5, 6]. Generally speaking, source of instability in these processes is appearance of some tachyonic modes in the spectrum of these objects. It then makes sense to study them in a field theory which includes those modes. In this regard, it has been shown by A. Sen that an effective action of Born-Infeld type proposed in [7, 8, 9, 10] can capture many properties of the decay of non-BPS D_p -branes in string theory [2, 3].

Recently, unstable objects have been used to study spontaneous chiral symmetry breaking in holographic model of QCD [11, 12, 13]. In these studies, flavor branes introduced by placing a set of parallel branes and antibranes on a background dual to a confining color theory [14]. Detailed study of brane-antibrane system reveals when brane separation is smaller than the string length scale, spectrum of this system has two tachyonic modes [15]. The effective action should then include these tachyonic modes because they are the most important modes which rule the dynamics of the system.

A proposal by A. Sen for $D_p\bar{D}_p$ effective action when branes are coincident is [16]

$$S = - \int d^{p+1} \sigma V(|\tau|) \left(\sqrt{-\det \mathbf{A}^{(1)}} + \sqrt{-\det \mathbf{A}^{(2)}} \right), \quad (1)$$

where

$$\mathbf{A}_{\mu\nu}^{(n)} = \eta_{\mu\nu} + 2\pi\alpha' F_{\mu\nu}^{(n)} + \pi\alpha' (D_\mu\tau(D_\nu\tau)^* + D_\nu\tau(D_\mu\tau)^*) . \quad (2)$$

which is a generalization of tachyon DBI action [7, 8, 9, 10]. This action has a vortex solution whose world-volume action is given by the action of stable D_{p-2} -brane [16]. In order to extend the above action to the action of non-coincident branes, it has been proposed in [17] that the effective action of $D_p\bar{D}_p$ might be derived from the effective action of two non-BPS D-branes by projecting it with $(-1)^{F_L}$ where F_L is the spacetime left-handed fermion number. Two non-BPS branes, on the other hand, may be described effectively by the non-abelian generalization of the tachyon DBI action. This action should extend the abelian $U(1)$ gauge symmetry of one non-BPS brane to non-abelian $U(2)$ symmetry of two non-BPS D-branes[8]. The non-abelian action can then be found by converting the open string fields to matrix form, changing the ordinary derivative to covariant derivative and performing a trace over the matrices. Various trace prescriptions give different non-abelian theories. In this paper, we would like to consider two trace prescriptions. Ordinary trace and symmetric trace prescription. In the first case, we shall show that the resulting action is consistent with the above action when branes are coincident. In the second case, we shall show that the action is not consistent with the above action. However, the good point about this latter action is that it is consistent with the S-matrix element calculations.

In the next section we shall find the two effective actions for the $D_9\bar{D}_9$ system by projecting the Chan-Paton factors of the open string fields in the non-abelian tachyon DBI

action of two non-BPS branes with $(-1)^{F_L}$. In this section, we compare the two proposal for the effective action and show that they are not the same action. In particular, the symmetric trace action has coupling between $F^{(1)}$ and $F^{(2)}$ whereas there is no such couplings in the ordinary trace action. In section 3, we will find the effective actions of the $D_p\bar{D}_p$ system for $p < 9$ by using the consistency of the effective actions with T-duality transformations. In this section we will show that even the $D_p\bar{D}_p$ tachyon potential is different in the two effective actions.

2 $D_9\bar{D}_9$ effective action

The effective action for describing the dynamics of one non-BPS D_p -brane, and its coupling to gravity and world-volume gauge field is given by [7, 8, 9, 10]:

$$S = - \int d^{p+1} \sigma V(T) e^{-\Phi} \sqrt{-\det(P[g_{ab} + B_{ab}] + 2\pi\alpha' F_{ab} + 2\pi\alpha' \partial_a T \partial_b T)}, \quad (3)$$

where $V(T)$ is the tachyon potential. Here g_{ab}, B_{ab}, Φ and A_a are the spacetime metric, antisymmetric Kalb-Ramond tensor, dilaton and the gauge field, respectively. In above action $P[\cdot \cdot \cdot]$ is also the pull-back of the closed string fields. For example, $P[\eta_{ab}] = \eta_{\mu\nu} \partial_a X^\mu \partial_b X^\nu = \eta_{ab} + \partial_a X^i \partial_b X_i$ in the static gauge¹. There are different proposal for the tachyon potential [18, 5]. The tachyon potential which is consistent with S-matrix element calculation is $V(T) = T_p(1 + \pi\alpha' m^2 T^2 + \frac{1}{2!}(\pi\alpha' m^2 T^2)^2 + O(T^6))$ where $m^2 = -1/(2\alpha')$. This potential is also consistent with the potential in boundary superstring field theory [19].

Now consider $N = 2$ non-BPS D_p -branes. They may be described effectively by non-abelian extension of the above action. To find the non-abelian action for $p < 9$, one may consider first the non-abelian action for $p = 9$ case which has no transverse scalar field, and then use the T-duality transformations to find the effective action for any p . We consider the following two non-abelian extensions:

$$S_1 = -\text{Tr} \int d^{10} \sigma V(T) e^{-\Phi} \sqrt{-\det(g_{\mu\nu} + B_{\mu\nu} + 2\pi\alpha' F_{\mu\nu} + \pi\alpha' [D_\mu T D_\nu T + D_\nu T D_\mu T])} \quad (4)$$

where we have written the kinetic term in the symmetric form to make the integrand a Hermitian matrix², and

$$S_2 = -\text{STr} \int d^{10} \sigma V(T) e^{-\Phi} \sqrt{-\det(g_{\mu\nu} + B_{\mu\nu} + 2\pi\alpha' F_{\mu\nu} + 2\pi\alpha' D_\mu T D_\nu T)} \quad (5)$$

¹Our index convention is that $\mu, \nu, \dots = 0, 1, \dots, 9$; $a, b, \dots = 0, 1, \dots, p$ and $i, j, \dots = p+1, \dots, 9$.

²Another nonabelian extension of action (3) has been considered in [17] in which the trace has been taken to be the ordinary trace and the kinetic term has been written in symmetric form at the end after applying the T-duality transformation.

here the symmetric trace make the integrand to be a Hermitian matrix. In above, the gauge field strength and covariant derivative of the tachyon are

$$\begin{aligned} F_{\mu\nu} &= \partial_\mu A_\nu - \partial_\nu A_\mu - i[A_\mu, A_\nu], \\ D_\mu T &= \partial_\mu T - i[A_\mu, T]. \end{aligned}$$

Obviously both actions (4) and (5) have $U(2)$ gauge symmetry and reduce to (3) for $N = 1$. The trace in S_1 is the usual trace whereas the trace in S_2 is the symmetric trace. That is, one has to first expand the square root and the tachyon potential and then make each term of the expansion completely symmetric between all non-abelian expressions of the form $F_{\mu\nu}$, $D_\mu T$ and the individual T of the tachyon potential. Only after this rearrangement, one has to perform the trace. Various couplings in the action (5) are consistent with the appropriate disk level S-matrix elements in string theory [8, 20, 21]. In particular, the calculation in [21] shows that the consistency is hold only if one uses the symmetric trace prescription.

The proposal for the effective action of D_9 -brane anti- D_9 -brane system [17] is to project the effective action of two non-BPS D_9 -brane with $(-1)^{F_L}$. All fields in the non-abelian tachyon DBI action are invariant under the $(-1)^{F_L}$ projection. However, the Chan-Paton matrices is not invariant under this projection [22]. It projects the Chan-Paton matrices of two non-BPS D_9 -brane to the following matrices:

$$A_\mu = \begin{pmatrix} A_\mu^{(1)} & 0 \\ 0 & A_\mu^{(2)} \end{pmatrix}, \quad T = \begin{pmatrix} 0 & \tau \\ \tau^* & 0 \end{pmatrix}. \quad (6)$$

The superscripts (1) and (2) refer to the open string fields with both ends on brane 1 and 2, respectively. $\tau(\tau^*)$ refers to the tachyon with one end on brane 1(2) and the other end on brane 2(1). Since there is no off-diagonal terms for the gauge field, the theory has gauge symmetry $U(1) \times U(1)$. For above matrices, one finds

$$F_{\mu\nu} = \begin{pmatrix} F_{\mu\nu}^{(1)} & 0 \\ 0 & F_{\mu\nu}^{(2)} \end{pmatrix}, \quad D_\mu T = \begin{pmatrix} 0 & D_\mu \tau \\ (D_\mu \tau)^* & 0 \end{pmatrix} \quad (7)$$

where $F_{\mu\nu}^{(i)} = \partial_\mu A_\nu^{(i)} - \partial_\nu A_\mu^{(i)}$ and $D_\mu \tau = \partial_\mu \tau - i(A^{(1)} - A^{(2)})\tau$.

Now one has to perform the traces. Since the matrices F_μ , $D_\mu T$ and T do not commute, one can not perform the trace in S_2 without expanding the square root and the tachyon potential. The trace in S_1 , on the other hand, is ordinary trace and can be performed for the above matrices without expanding the action. Now using the fact that the tachyon potential is an even function of T , one finds that for the above matrices the tachyon potential becomes $V(T) = V(|\tau|)I$ and the covariant derivative term in the action (4) becomes $D_\mu T D_\nu T + D_\nu T D_\mu T = (D_\mu \tau (D_\nu \tau)^* + (D_\mu \tau)^* D_\nu \tau)I$. Hence, the action (4) reduces to a diagonal matrix which after performing the trace it becomes

$$S_1 = - \int d^{10} \sigma V(|\tau|) e^{-\Phi} \left(\sqrt{-\det \mathbf{A}^{(1)}} + \sqrt{-\det \mathbf{A}^{(2)}} \right), \quad (8)$$

where

$$\mathbf{A}_{\mu\nu}^{(n)} = g_{\mu\nu} + B_{\mu\nu} + 2\pi\alpha' F_{\mu\nu}^{(n)} + \pi\alpha' (D_\mu\tau(D_\nu\tau)^* + D_\nu\tau(D_\mu\tau)^*) . \quad (9)$$

This action is the one proposed in [16].

Now let us compare the above action with the symmetric trace action (5) for trivial closed string background *i.e.*, $g = \eta$, $B = 0$, $\Phi = 0$. Using the following expansion, one can expand the square root in (8) and (5) to produce various interacting terms

$$\begin{aligned} \sqrt{-\det(M_0 + M)} &= \sqrt{-\det(M_0)} \left(1 + \frac{1}{2} \text{Tr}(M_0^{-1}M) - \frac{1}{4} \text{Tr}(M_0^{-1}MM_0^{-1}M) \right. \\ &\quad + \frac{1}{8} (\text{Tr}(M_0^{-1}M))^2 + \frac{1}{6} \text{Tr}(M_0^{-1}MM_0^{-1}MM_0^{-1}M) \\ &\quad \left. - \frac{1}{8} (\text{Tr}(M_0^{-1}M)) \text{Tr}(M_0^{-1}MM_0^{-1}M) + \frac{1}{48} (\text{Tr}(M_0^{-1}M))^3 + \dots \right) \end{aligned}$$

The terms involving two gauge fields and two tachyons are the following:

$$\begin{aligned} \mathcal{L}_1 &= -T_9(2\pi\alpha') \left(m^2|\tau|^2 + D\tau \cdot (D\tau)^* - \frac{\pi\alpha'}{2} F^{(1)} \cdot F^{(1)} \right) + T_9(\pi\alpha')^3 \times \\ &\quad \left(D\tau \cdot (D\tau)^* F^{(1)} \cdot F^{(1)} + m^2|\tau|^2 F^{(1)} \cdot F^{(1)} - 2F^{(1)\mu\alpha} F_{\alpha\beta}^{(1)} [D^\beta\tau(D_\mu\tau)^* + (D^\beta\tau)^* D_\mu\tau] \right) \end{aligned} \quad (10)$$

There are similar terms for $F^{(2)}$. Note that there is no coupling between $F^{(1)}$ and $F^{(2)}$. The two gauge fields and two tachyons from expanding the action (5) are

$$\begin{aligned} \mathcal{L}_2 &= -T_9(\pi\alpha') \text{STr} \left(m^2 T^2 + D_\mu T D^\mu T - \pi\alpha' F_{\mu\nu} F^{\nu\mu} \right) + T_9(\pi\alpha')^3 \times \\ &\quad \times \text{STr} \left(D^\alpha T D_\alpha T F_{\mu\nu} F^{\nu\mu} + m^2 T^2 F_{\mu\nu} F^{\nu\mu} - 4F^{\mu\alpha} F_{\alpha\beta} D^\beta T D_\mu T \right) \end{aligned} \quad (11)$$

Writing the symmetric trace in term of ordinary trace, one finds

$$\begin{aligned} \mathcal{L}_2 &= -T_9(\pi\alpha') \text{Tr} \left(m^2 T^2 + D_\mu T D^\mu T - \pi\alpha' F_{\mu\nu} F^{\nu\mu} \right) + T_9(\pi\alpha')^3 \times \\ &\quad \text{Tr} \left(\frac{2}{3} D^\alpha T D_\alpha T F_{\mu\nu} F^{\nu\mu} + \frac{1}{3} D^\alpha T F_{\mu\nu} D_\alpha T F^{\mu\nu} + \frac{2m^2}{3} T^2 F_{\mu\nu} F^{\nu\mu} + \frac{m^2}{3} T F_{\mu\nu} T F^{\mu\nu} \right. \\ &\quad \left. - \frac{4}{3} F^{\mu\alpha} F_{\alpha\beta} D^\beta T D_\mu T - \frac{4}{3} F_{\alpha\beta} F^{\mu\alpha} D^\beta T D_\mu T - \frac{4}{6} F^{\mu\alpha} D^\beta T F_{\alpha\beta} D_\mu T \right. \\ &\quad \left. - \frac{4}{6} F_{\alpha\beta} D^\beta T F^{\mu\alpha} D_\mu T \right) \end{aligned} \quad (12)$$

Note that the above matrix is Hermitian. Inserting the matrices T , $F_{\mu\nu}$ and $D_\mu T$ from (6) and (7) and performing the trace, one finds

$$\mathcal{L}_2 = -T_9(2\pi\alpha') \left(m^2|\tau|^2 + D\tau \cdot (D\tau)^* - \frac{\pi\alpha'}{2} (F^{(1)} \cdot F^{(1)} + F^{(2)} \cdot F^{(2)}) \right) + T_9(\pi\alpha')^3 \times$$

$$\begin{aligned}
& \times \left(\frac{2}{3} D\tau \cdot (D\tau)^* \left(F^{(1)} \cdot F^{(1)} + F^{(1)} \cdot F^{(2)} + F^{(2)} \cdot F^{(2)} \right) \right. \\
& + \frac{2m^2}{3} |\tau|^2 \left(F^{(1)} \cdot F^{(1)} + F^{(1)} \cdot F^{(2)} + F^{(2)} \cdot F^{(2)} \right) \\
& \left. - \frac{4}{3} ((D^\mu \tau)^* D_\beta \tau + D^\mu \tau (D_\beta \tau)^*) \left(F^{(1)\mu\alpha} F_{\alpha\beta}^{(1)} + F^{(1)\mu\alpha} F_{\alpha\beta}^{(2)} + F^{(2)\mu\alpha} F_{\alpha\beta}^{(2)} \right) \right)
\end{aligned}$$

The first line is like the corresponding terms in (10), however, the other couplings are not the same as in (10). In particular, there is coupling between $F^{(1)}$ and $F^{(2)}$. Obviously when tachyon is zero, the two action become identical because the matrix F is diagonal, hence, the symmetric trace and ordinary trace are the same.

3 $D_p \bar{D}_p$ effective action

The action for $D_p \bar{D}_p$ system can be found from $D_9 \bar{D}_9$ by using the consistency of the action with T-duality transformations. T-duality transformations in $i = p+1, \dots, 9$ directions of the $D_9 \bar{D}_9$ world volume converts the $D_9 \bar{D}_9$ to $D_p \bar{D}_p$, the gauge fields in those directions to $\tilde{A}_i^{(1)} = X^{(1)i}/2\pi\alpha'$, $\tilde{A}_i^{(2)} = X^{(2)i}/2\pi\alpha'$ and leave unchanged the tachyons. The T-duality of S_2 is the non-abelian tachyon DBI action that has been found in [8]. The corresponding action for $D_p \bar{D}_p$ is

$$\begin{aligned}
S_2 = & - \int d^{p+1} \sigma \text{STr} \left(V(T) \sqrt{\det(Q^i_j)} \right. \\
& \left. \times e^{-\Phi} \sqrt{-\det(P[E_{ab} + E_{ai}(Q^{-1} - \delta)^{ij} E_{jb}] + 2\pi\alpha' F_{ab} + T_{ab})} \right), \tag{13}
\end{aligned}$$

where $E_{\mu\nu} = g_{\mu\nu} + B_{\mu\nu}$. The indexes in this action are raised and lowered by E^{ij} and E_{ij} , respectively. The matrices Q^i_j and T_{ab} are

$$\begin{aligned}
Q^i_j &= I\delta^i_j - \frac{1}{2\pi\alpha'} L^i L^k E_{kj}, \\
T_{ab} &= 2\pi\alpha' D_a T D_b T + D_a T L^i (Q^{-1})_{ij} L^j D_b T \\
&\quad + iE_{ai} (Q^{-1})^i_j L^j D_b T - iD_a T L^i (Q^{-1})_i^j E_{jb} \\
&\quad + i\partial_a X^i (Q^{-1})_{ij} L^j D_b T - iD_a T L^i (Q^{-1})_{ij} \partial_b X^j. \tag{14}
\end{aligned}$$

The trace in the action (13) should be completely symmetric between all matrices of the form $F_{ab}, \partial_a X^i, D_a T, L^i$, individual T of the tachyon potential and individual X^i of the Taylor expansion of the closed string fields in the action[23]. The matrices F_{ab} , $D_a T$ and T are those appear in (6) and (7), and the matrices $\partial_a X^i$ and L^i are

$$\partial_a X^i = \begin{pmatrix} \partial_a X^{(1)} & 0 \\ 0 & \partial_a X^{(2)} \end{pmatrix}, \quad L^i = [X^i, T] = \ell^i \begin{pmatrix} 0 & \tau \\ -\tau^* & 0 \end{pmatrix} \tag{15}$$

where $\ell^i = X^{(1)i} - X^{(2)i}$ is the distance between the two branes.

The T-duality of S_1 is obtained by performing the T-duality for each term of (8) which has no matrix. Under T-duality transformation, the covariant derivative of tachyon becomes $\widetilde{D}_i \widetilde{\tau} = -i\ell^i \tau / 2\pi\alpha'$. Using the same steps as those in [24, 8] for finding the T-dual action (13), one finds

$$S_1 = - \int d^{p+1} \sigma V(|\tau|) \sqrt{\det(Q)} e^{-\Phi} \left(\sqrt{-\det \mathbf{A}^{(1)}} + \sqrt{-\det \mathbf{A}^{(2)}} \right), \quad (16)$$

where

$$\begin{aligned} \mathbf{A}_{ab}^{(n)} &= P^{(n)} \left[E_{ab} - \frac{|\tau|^2}{2\pi\alpha' \det(Q)} E_{ai} \ell^i \ell^j E_{jb} \right] + 2\pi\alpha' F_{ab}^{(n)} \\ &+ \frac{1}{\det(Q)} \left(\pi\alpha' [D_a \tau (D_b \tau)^* + D_b \tau (D_a \tau)^*] \right. \\ &+ \frac{\ell \cdot \ell}{4} [\tau (D_a \tau)^* + \tau^* D_a \tau] [\tau (D_b \tau)^* + \tau^* D_b \tau] \\ &+ \frac{i}{2} [E_{ai} + \partial_a X^{(n)j} E_{ji}] \ell^i [\tau (D_b \tau)^* - \tau^* D_b \tau] \\ &\left. - \frac{i}{2} [\tau (D_a \tau)^* - \tau^* D_a \tau] \ell^i [E_{ib} + E_{ij} \partial_b X^{(n)j}] \right), \end{aligned} \quad (17)$$

where $\det(Q) = 1 + |\tau|^2 \ell \cdot \ell / 2\pi\alpha'$. In the above equation $P^{(n)}[\dots]$ means pull-back of closed string fields on the n -th brane, *e.g.*, $P^{(1)}[\eta_{ab}] = \eta_{ab} + \partial_a X_i^{(1)} \partial_b X_j^{(1)} \eta^{ij}$. For simplicity we have assumed that the closed string fields have no X^i dependency³.

Now let us compare the $D_p \bar{D}_p$ potential in the above action with the potential in (13). For small $|\tau|$ the $D_p \bar{D}_p$ potential in the above action has the following expansion:

$$2V(|\tau|) \sqrt{\det(Q)} = 2T_p \left(1 + \frac{2\pi\alpha'}{2} \left(\frac{\ell \cdot \ell}{(2\pi\alpha')^2} - \frac{1}{2\alpha'} \right) |\tau|^2 - \frac{1}{8\alpha'} \ell^2 \tau^4 + \dots \right). \quad (18)$$

The second term in the second parentheses above is the mass squared of the tachyon and the first term is the mass squared of the string stretched between two branes, *i.e.*, $(\text{tension})^2 \times (\text{length})^2$. Note that potential had local minimum at $|\tau| = 0$ only when $\ell > \sqrt{2\pi^2\alpha'}$. The corresponding terms in the action S_2 is

$$\text{STr} \left(V(T) \sqrt{\det(Q^i_j)} \right) = 2T_p \left(1 + \frac{2\pi\alpha'}{2} \left(\frac{\ell \cdot \ell}{(2\pi\alpha')^2} - \frac{1}{2\alpha'} \right) |\tau|^2 - \frac{1}{24\alpha'} \ell^2 \tau^4 + \dots \right) \quad (19)$$

³ The difference between the above action and the one considered in [17] is that the terms in the third line of (17) is missing in [17]. This results from the different construction of the non-abelian actions. In [17], one first simplifies $2\pi\alpha' D_a T D_b T + D_a T L^i (Q^{-1})_{ij} L^j D_b T = 2\pi\alpha' D_a T D_b T / \det(Q)$ and then, in order to have a real action, one makes the terms $D_a T D_b T$ and $D_a T L^i$ each symmetric. Whereas in the above action one first makes them symmetric and then simplifies the result.

While the first three terms in (18) and (19) are the same, the last terms are different. This results from the symmetric trace prescription, *i.e.*, $S\text{Tr}(T^2LL) = \frac{2}{3}\text{Tr}(TTLL) + \frac{1}{3}\text{Tr}(TLTL)$. The sign of the two terms are different after performing the trace, whereas in (18) both have the same sign. For other terms, the coefficient of τ^n is the same for both potentials, however, because of the symmetric trace, the coefficient of $\ell^m\tau^n$ in (19) is smaller than the corresponding term in (18).

As we mentioned in the Introduction section, a good feature of S_1 is that it has a vortex solution whose world volume action is given by the DBI action of stable D_{p-2} -brane [16]. In that calculation the ansatz for the fields is that $F^{(1)} = -F^{(2)}$, $T \neq 0$ and all other fields are zero. For this assumption the two actions S_1 and S_2 are not identical. So the vortex solution of S_1 is not a solution of S_2 . On the other hand, if S_2 is going to be the effective action of brane-antibrane system, it should have vortex solution. It would be interesting to find such solution.

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